Virtually Isotropic Transmission Media with Fiber Raman Amplifier

Sergey Sergeyev, Sergei Popov, Ari T. Friberg

***Abstract* — We report a theoretical study and simulations of a novel fiber-spin tailoring technique to suppress the polarization impairments, namely polarization mode dispersion (PMD) and polarization dependent gain (PDG), in fiber Raman amplifiers. Whereas use of depolarizer or multiplexing pump laser diodes with a final degree of pump polarization of 1% for periodically spun fiber results in PDG of about 0.3 dB, we demonstrate that application of just a two-section fiber (where the first part is short and has no spin, and the second one is periodically spun) can reduce the PDG to as low as below 0.1 dB.**

***Index Terms*—Optical fiber amplifiers, Raman scattering.**

I. Introduction

Polarization impairments are among major factors limiting the progress in further increase of transmission rates and overall capacity of the next generation of optical networks based on distributed fiber Raman amplification. For example, application of ultra-long 120 km fiber Raman laser creates broadband quasi-lossless fiber spans with simultaneous spatial and spectral transparency [1, 2]. However, further application of this technology for ultra-high bit-rate communication systems requires the design of quasi-isotropic media, i.e., addressing the issue of polarization impairments in a form of polarization mode dispersion (PMD) and Raman polarization dependent gain (PDG). PMD leads to pulse broadening caused by varying group velocities for the pulses with different states of polarization (SOPs) (Fig. 1) [3-8]. PDG is the dependence of Raman gain on the input signal SOP (Fig. 2) [9-15].

By the traditional approach, spinning the fiber periodically, it is possible to reduce PMD to below 0.04 ps/km$^{1/2}$ (Corning LEAF® fiber, manufactured by Corning Inc., USA [6, 7]), but this is accompanied with a simultaneous increase in Raman PDG [13]. All the existing PDG mitigation schemes are rather expensive (polarization multiplexing of pump laser diodes, application of a depolarizer) or not very effective (backward pumping) in the case of low PMD fibers [9, 12, 16].

To develop a reliable technique for simultaneous mitigation of both PMD and PDG, an advanced vector model of a fiber Raman amplifier has to be employed, accounting also for the random birefringence and arbitrary spin profile of the fiber. Sergeyev et al. [13] have recently put forward such a model, which takes the form of ordinary differential equations for the gain of the fiber Raman amplifier as a function of pump and signal states of polarization (SOP), PMD parameter, and the parameters of fiber spinning. Using this model, it was shown that it is possible to mitigate both PDG and PMD by adopting a fiber with a particular spin profile or, more specifically, a two-section fiber ('two-section approach') in which the first section has no spin and the second one is periodically spun [13]. As a result, PDG and PMD in 10 km of dispersion compensation fiber (DCF) can be suppressed to 0.13 dB and 0.032 ps/km$^{1/2}$, respectively [13].

To suppress PMD and PDG further, and thus to develop quasi-isotropic transmission media of 50 km length, we report herein on a novel approach to optimize the parameters of the first section of the fiber, viz., its correlation length and PMD. In addition, we compare our new technique with the generic method of PDG suppression that is based on the application of a depolarizer [9, 16].

II. Optimization of Parameters for 'Two-Section Approach'

For a high PMD fiber, for example a polarization maintaining (PM) fiber, if the pump wave is polarized along one of the birefringence axes, the parallel orientation of the signal corresponds to maximum Raman gain, while the orthogonal orientation results in minimum gain [11]. The difference between two gains (in dB units) is a quantitative measure of polarization dependent gain which takes the maximum value for this case [11]. If initially the pump field is equally shared between the two orthogonal states of polarization, the pump SOP evolves through all the possible polarization states and returns to its original state after a beat length L_b. On average, the pump power is the same along both orthogonal axes. Hence, there is no difference in the Raman gain values and the PDG takes on the minimum value which equals zero [11]. Unlike a PM fiber, the random birefringence in a single mode fiber can be represented in terms of a *fixed modulus model* (FMM), where the length of the birefringence vector is fixed and its orientation is driven by a white-noise process, and a more complex *random modulus model* (RMM), in which both

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the orientation and the length of the birefringence vector change randomly [13]. Poole and Wagner [3] have shown that the so-called principal states of polarization (PSPs) are a key concept in analyzing PMD in fibers with randomly varying birefringence. The PSPs correspond to two orthogonal states of polarization at the input that yield polarization states that are independent of frequency to first order at the output. For a PM fiber, the PSPs coincide with the fast and slow axes and the input and output PSPs are the same. For a fiber with random birefringence (SM fiber), the input and output PSPs are different. In view of this, we demonstrated experimentally and theoretically in our previous publications that, similar to PM fibers, PDG in SM fibers takes on its maximum value if the pump SOP is oriented along a PSP, and a small minimum one (different from zero) if the pump SOP is equally shared initially between the PSPs [12-15].

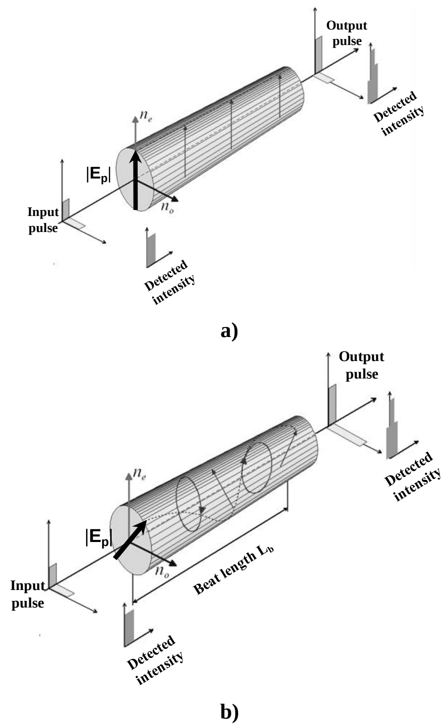

Figure 1. Optical pulse distortion in terms of differential group delay DGD, caused by polarization mode dispersion PMD and polarization dependent gain PDG, in a Raman amplifier with fixed birefringence, e.g., a polarization maintaining (PM) fiber. (a) Pump electric-field vector is oriented along a birefringence axis; (b) pump electric-field is equally shared between the two orthogonal states of polarization.

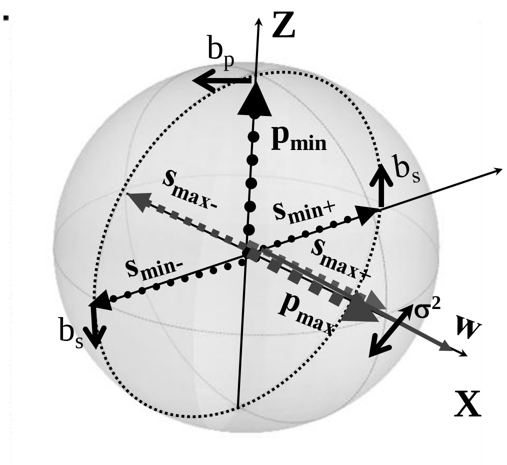

Figure 2. Evolution of the pump (**p**) and signal (**s**) states of polarization on the Poincaré sphere, as well as the rotation of the local birefringence vector **w**. Vectors **p** and **s** rotate around the local axis **w** at rates b_p and b_s , while vector **w** rotates randomly in the equatorial plane at the rate $\sigma = L_c^{-1/2}$ (L_c is the correlation length). Maximum PDG: initial orientations of the pump SOP along the PSP, i.e., $\mathbf{p}_{max}$ = (1, 0, 0), signal polarizations $\mathbf{s}_{max+}$ = (1, 0, 0) giving the maximum Raman gain, and $\mathbf{s}_{max-}$= (-1, 0, 0) the minimum gain. Minimum PDG: pump power is equally shared between PSPs, for example $\mathbf{p}_{min}$ = (0, 0, 1) , signal polarizations $\mathbf{s}_{min+}$ = (0, 1 0) leading to the maximum Raman gain, and $\mathbf{s}_{min-}$= (0, -1, 0) to the minimum gain. These orientations correspond to the minimum polarization dependent gain (PDG) for the case of oscillatory behavior of the pump to signal SOP projection, i.e., when b_p-b_s is much higher than the de-correlation rate L_c^{-1}.

However, a SM fiber with PMD suppressed by periodic spinning becomes isotropic, i.e., without absolute anisotropy axis with reference to the whole fiber. As a result, the Raman gain depends only on the relative orientation between the input signal and the pump SOPs, which is not changing along the length of the isotropic fiber: co-polarized pump and signal waves give the upper limit of maximum Raman gain and cross-polarized waves result in the lower limit of minimum gain as a function of the PMD value. Finally, maximum and minimum PDGs converge and approach the upper limit of PDG which can exceed 20 dB [13].

The vector model describing the polarization dependence of the Raman gain in fibers with random or regular birefringence can instructively be demonstrated using the Poincaré sphere. Here, the states of the signal and pump polarization are considered in terms of vectors $\boldsymbol{s}=(s_1,s_2,s_3)$ and $\boldsymbol{p}=(p_1,p_2,p_3)$ pointing to positions on the Poincaré sphere (Fig. 2). Fiber birefringence can be presented as a rotation of the $\boldsymbol{s}$ and $\boldsymbol{p}$ vectors on the Poincaré sphere around the birefringence vector **w**, which, in turn, oscillates regularly due to the periodic fiber spinning or/and randomly due to random birefringence. These regular or random oscillations of the birefringence vector lead to the slowing down of the signal SOP's rotation, i.e., to a suppression of PMD.

As is illustrated in Fig. 2, the *signal* and *pump* states of polarization revolve on the Poincaré sphere in the same direction but at different rates b_s and b_p ($b_i=\pi/L_{bi}$ is the birefringence strength, L_{bi} is the beat length) around the birefringence vector **w**. If the difference b_p-b_s is much higher than the de-correlation rate $1/L_c$, then $\boldsymbol{s}$ and $\boldsymbol{p}$ vectors reach mutually parallel and orthogonal orientations, and oscillatory behavior occurs for the averaged projection of the signal SOP on the pump SOP, i.e., for $\langle x\rangle = \langle \boldsymbol{s}\cdot\boldsymbol{p}\rangle$ [14]. As a result, the projections corresponding to the max/min Raman gain, i.e., $\langle x_{max}\rangle$ and $\langle x_{min}\rangle$, oscillate in anti-phase along the fiber and merge at distances of $z_n = nT/2$, where T is the spatial period, and n is an integer [14]. It is quite clear that for a low PMD fiber such a rotation is absent. This fiber can be periodically spun with the spinning profile (in units of rad)

$$A(z) = A_0 \sin\frac{2\pi z}{p}, \tag{1}$$

where A_0 and p are the spinning amplitude and period, and z is a distance along the fiber. Therefore, if we combine a short-length fiber ($L_1 = z_1$) without spin with a long periodically spun fiber with the length of $L_2 >> L_1$, the projections will be the same from the point of merging to the end of the fiber. In this case, as shown in [13], PDG is approximately equal to $<x_{max}> - <x_{min}>$ averaged over the length of the fiber. This means that the PDG depends on the parameters of the fiber's first section only and can be minimized [13]. The minimum required length of the first section of fiber L_1 has been found as follows [13]

$$L_1 \approx 2\pi L_c / \sqrt{4\left[\pi D_p^{(1,un)} c\sqrt{2L_c}\left(1/\lambda_p - 1/\lambda_s\right)\right]^2 - 1/4}, \quad (2)$$

where λ_p and λ_s are the pump and signal wavelengths, $D_p^{(1,un)}$ is the PMD parameter of the first section of the fiber, and L_c is the correlation length [13]. For a two-section fiber, the mean-square differential group delay (DGD) $\sqrt{\langle\Delta\tau_{ts}^2\rangle}$ depends on the DGDs of the fiber without spin $\langle\Delta\tau_{un}^2\rangle$ and the periodically spun fiber $\langle\Delta\tau_{ps}^2\rangle$ as follows

$$\sqrt{\langle\Delta\tau_{ts}^2(L)\rangle} = \sqrt{\langle\Delta\tau_{un}^2(L_1)\rangle + \langle\Delta\tau_{ps}^2(L_2)\rangle}\,. \quad (3)$$

The *spin induced reduction factor* (SIRF) is defined as [5]

$$SIRF = \frac{\sqrt{\langle\Delta\tau_{ts}^2(L)\rangle}}{\langle\Delta\tau_{un}^2(L)\rangle} = \frac{D_p^{ts}(L)}{D_p^{un}(L)}, \quad (4)$$

where $\langle\Delta\tau_{un}^2(L)\rangle = D_p^{(un)}\sqrt{(\exp(-L/L_c) - 1)L_c + L}$, and $D_p^{(un)}$, $D_p^{(ts)}$ are the PMD parameters for the fiber without spinning and the two-section fiber [13]. If the initial (before spinning) PMD for the periodically spun fiber coincides with the PMD of the first fiber section, i.e., $D_p^{(2,sp)} = D_p^{(1,un)}$, and if $L \gg L_c$ and $\langle\Delta\tau_{un}^2(L_1)\rangle \gg \langle\Delta\tau_{ps}^2(L_2)\rangle$, the SIRF for the two-section section fiber can be calculated as [13]

$$SIRF = \sqrt{(\exp(-L_1/L_c) - 1)\, L_c/L + L_1/L}\,. \quad (5)$$

Otherwise, the SIRF is calculated as follows [5]

$$\frac{dSIRF^2}{dz'} = \epsilon_1\langle\hat{\Omega}_1\rangle,$$

$$\frac{d\langle\hat{\Omega}_1\rangle}{dz'} = -\langle\hat{\Omega}_1\rangle + 2\alpha(z')L_c\langle\hat{\Omega}_2\rangle + 1,$$

$$\frac{d\langle\hat{\Omega}_2\rangle}{dz'} = -2\alpha(z')L_c\langle\hat{\Omega}_1\rangle - \langle\hat{\Omega}_2\rangle - \epsilon_2\langle\hat{\Omega}_3\rangle,$$

$$\frac{d\langle\hat{\Omega}_3\rangle}{dz'} = \epsilon_2\langle\hat{\Omega}_2\rangle. \quad (6)$$

Here $z' = z/L_c$, $\langle\hat{\Omega}_i\rangle$ $(i=1,2,3)$ are the averaged and normalized components of the PMD vector, $\epsilon_1 = L_c/L, \epsilon_2 = (2\pi L_c)/L_b$, and $\alpha(z') = \partial A(z')/\partial z'$ is the spin rate.

It is well known that the SIRF for the periodic spin rate can reach the minimum value of less than 0.01 for the phase-matching condition $A_0 \approx 1.2$ [5]. It means that Eq. (5) along with Eq. (2) can be used for optimization of the first section of the fiber in the context of parameters L_c, L_1, and $D_p^{(1,un)}$. As a result, we obtain

$$\sqrt{L_c}D_p^{(1,un)} = \frac{1}{4\pi(1/\lambda_p - 1/\lambda_s)}. \quad (7)$$

III. Two-section Approach vs Depolarizer Application for Mitigation of PMD and PDG

To justify the method of the first section's optimization, we have used Eqs. (6) to find the SIRF and the advanced model of the fiber Raman amplifier for a two-section fiber [13]. We also have used both models to calculate PDG and PMD in the case when a depolarizer is applied.

It is known from experimental measurements that the PDG for backward pumping is significantly lower than for forward pumping, while the average gain is higher [9, 12]. Hence, to consider the more instructive and practical example, here we deal with forward pumping. We consider also a two-section fiber where the first section of length L_1 has no spin and the second one of length L_2 is periodically spun. In our approach, we make use of the FMM, which is simpler but nonetheless demonstrates results for the SIRF similar to those obtained with the RMM for the case $(p/L_b)^2 \ll 1$ [8].

We further neglect both pump depletion and the signal-induced cross-phase modulation (XPM), which is valid when the pump power is much larger than the signal power. Additionally, the pump induced XPM, i.e., term $\varepsilon_{sp}\boldsymbol{P}\times\boldsymbol{S}$, is eliminated by a specific transformation [10]. It follows that PDG is a function of the length of the signal Stokes vector, which is invariant under transformations such as the one employed in [10]. Thus, nonlinear phase rotation caused by pump-induced XPM has no affect on polarization dependent gain [10]. Next, we choose the reference frame in the Stokes space in such a way that the *x* axis coincides with the input principal state of polarization. In view of notations in Fig. 2, there are two pump SOPs for which PDG take the maximum and minimum value. The first SOP is oriented along PSP, i.e., $\boldsymbol{p}_{max} = (1, 0, 0)$, while the second one is arbitrary, for example $\boldsymbol{p}_{min} = (0, 0, 1)$, which provides equal sharing of the pump power between the two PSPs [13-15]. As follows from [10, 13-15], the max/min of PDG can be calculated as

$$PDG = 10log\left(\frac{\langle s_0^{max}\rangle}{\langle s_0^{min}\rangle}\right). \quad (8)$$

Here <…> denotes averaging over the birefringence fluctuations along the fiber.

The averaged length of the Poincaré vector $<s_0>$ at the fiber output is a function of the input pump and the signal SOPs and can be found from [12]:

$$\frac{d\langle s_0\rangle}{dz'} = \varepsilon_1 exp(-\varepsilon_2 z')\langle x\rangle,$$

$$\frac{d\langle x\rangle}{dz'} = \varepsilon_1 exp(-\varepsilon_2 z')\langle s_0\rangle - \varepsilon_3\langle y\rangle,$$

$$\frac{d\langle y\rangle}{dz'} = \varepsilon_3[\langle x\rangle - \tilde{p}_1(0)\tilde{s}_1(0)exp(-z')] - 2\alpha(z')L_c\langle u\rangle - \frac{\langle y\rangle}{2},$$

$$\frac{d\langle u\rangle}{dz'} = 2\alpha(z')L_c\langle y\rangle - \frac{\langle u\rangle}{2}. \quad (9)$$

Here $z' = z/L_c$, $\langle x\rangle = \langle\tilde{p}_1\tilde{s}_1 + \tilde{p}_2\tilde{s}_2 + \tilde{p}_3\tilde{s}_3\rangle$ is the projection of the signal SOP onto the pump SOP, $\langle y\rangle = \langle\tilde{p}_3\tilde{s}_2 - \tilde{p}_2\tilde{s}_3\rangle$, $\langle u\rangle = \langle\tilde{p}_3\tilde{s}_1 - \tilde{p}_1\tilde{s}_3\rangle$, $\varepsilon_1 = gP_{in}L_c/2$, $\varepsilon_2 = \alpha_s L_c$, $\varepsilon_3 = \pi D_p c\sqrt{2L_c}(1/\lambda_p - 1/\lambda_s)$, g is the Raman gain coefficient, P_{in} is the input pump power, and α_s and α_p are the signal and pump losses, respectively. Here $\tilde{\boldsymbol{p}}$ and $\tilde{\boldsymbol{s}}$ are the pump and signal SOPs in the reference frame in which $\widetilde{\boldsymbol{W}} = (2b_i, 0,0)$, i.e., the birefringence vector is oriented along PSP on the Poincaré sphere.

To justify the validity of FMM application we calculated the beat length as follows [4]:

$$L_b = \frac{\lambda_s\sqrt{2L_c}}{D_p c}, \quad (10)$$

and chose the fiber spinning amplitude to satisfy the relation $(p/L_b)^2 \ll 1$. To prove the feasibility of the two-section approach, we further calculated mean-square gain fluctuations (MSGF) of the two-section fiber $\langle\sigma_G^2(L)\rangle$ as follows

$$\langle\sigma_G^2(L)\rangle = \sqrt{\langle\sigma_G^2(L_1)\rangle + \langle\sigma_G^2(L_2)\rangle}, \quad (11)$$

where $\langle\sigma_G^2(L_1)\rangle$ and $\langle\sigma_G^2(L_2)\rangle$ are MSGFs for the first and the second fiber sections. As follows from [10, 15], $\langle\sigma_G^2(L_1)\rangle = (\langle s_0^2(L_1)\rangle - \langle s_0(L_1)\rangle^2)/\langle s_0(L_1)\rangle^2$ and $\langle s_0(L_1)\rangle^2$ is found from Eqs. (8) for $\alpha(z') = 0$ and $\langle s_0^2(L_1)\rangle$ is obtained from [15]

$$\frac{d\langle s_0^2\rangle}{dz'} = 2\varepsilon_1 exp(-\varepsilon_2 z')\langle s_0 x\rangle,$$

$$\frac{d\langle s_0 x\rangle}{dz'} = \varepsilon_1 exp(-\varepsilon_2 z')(\langle s_0^2\rangle + \langle x^2\rangle) - \varepsilon_3\langle s_0 y\rangle,$$

$$\frac{d\langle x^2\rangle}{dz'} = 2\varepsilon_1 exp(-\varepsilon_2 z')\langle s_0 x\rangle - 2\varepsilon_3\langle xy\rangle,$$

$$\frac{d\langle s_0 y\rangle}{dz'} = \varepsilon_1 exp(-\varepsilon_2 z')\langle xy\rangle + \varepsilon_3[\langle s_0 x\rangle - \langle s_0\rangle\tilde{p}_1(0)\tilde{s}_1(0)exp(-z')] - \frac{\langle s_0 y\rangle}{2},$$

$$\frac{d\langle xy\rangle}{dz'} = \varepsilon_1 exp(-\varepsilon_2 z')\langle s_0 y\rangle + \varepsilon_3[\langle x^2\rangle - \langle y^2\rangle - \langle x\rangle\tilde{p}_1(0)\tilde{s}_1(0)exp(-z')] - \frac{\langle xy\rangle}{2},$$

$$\frac{d\langle y^2\rangle}{dz'} = 2\varepsilon_3[\langle xy\rangle - \langle y^2\rangle - \langle y\rangle\tilde{p}_1(0)\tilde{s}_1(0)exp(-z')] - (\langle y^2\rangle - \langle u^2\rangle),$$

$$\frac{d\langle u^2\rangle}{dz'} = \langle y^2\rangle - \langle u^2\rangle. \quad (12)$$

Keeping in mind that $\alpha(z') \neq 0$, $\langle\sigma_G^2(L_2)\rangle$ cannot be found in the same way as $\langle\sigma_G^2(L_1)\rangle$, i.e., with the help of Eqs. (10). However, it was shown by Bettini et al. [17] for the case of Raman amplification in unidirectionally spun fibers that the maximum for the mean-square gain fluctuations is shifted to higher PMD values with increased fiber spinning frequency. It means that the gain fluctuations will be much lower for periodically spun fiber at the phase-matching condition $A_0 \approx 1.2$ than calculated from Eqs. (12).

Lin and Agrawal [10] demonstrated that the application of depolarizer results in transformation of coefficient ε_1 in Eqs. (9) and (12) as follows: $\varepsilon_1 \to \varepsilon_1 DOP$, where DOP is a degree of polarization at the depolarizer output.

IV. Results and Discussion

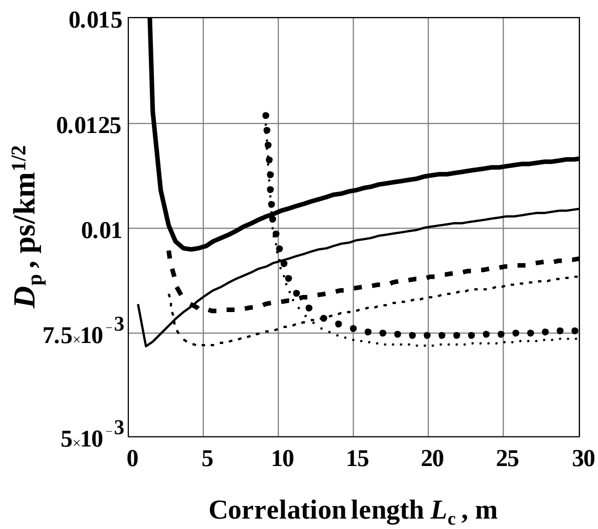

Figure 3. PMD parameter D_p as a function of correlation length L_c in the two-section fiber according to Eqs. (1,3,4-6) for $D_p^{(1)}$ = 0.05 ps·km$^{-1/2}$ (solid line), $D_p^{(1)}$ = 0.1 ps·km$^{-1/2}$ (dotted line), and $D_p^{(1)}$ = 0.2 ps·km$^{-1/2}$ (dashed line), calculated with the help of Eqs. (1,3,4-6) (thin lines) and with the help of Eqs. (1,3,5-6) (thick lines). Parameters: L=50 km, α_s=0.2 dB/km, λ_p=1460 nm, λ_s=1550 nm, g=2.3 W^{-1}km^{-1}, P=0.5 W.

First, we found the PMD value $D_p^{(1,un)}$, correlation length L_c, and the length L_1 for the first section from Eqs. (7) and (2) to provide minimum PMD value for the two-section fiber. We have used parameters typical for a single-mode-fiber based distributed fiber Raman amplifier: L=50 km, α_s=0.2 dB/km, λ_p=1460 nm, λ_s=1550 nm, g=2.3 dB W^{-1}km^{-1}, and P=0.5 W. Next, we calculated PMD values for the two-section fiber with the help of Eqs. (5) and (6) and accounting for Eq. (4). The results are shown in Fig. 3. In view of Eq. (7), one of the parameters $D_p^{(1,un)}$ or L_c can be chosen arbitrary, so we picked $D_p^{(1)}$ = 0.05, 0.1 and 0.2 ps·km$^{-1/2}$ (Fig. 3). As is seen from Fig. 3, Eqs. (2) and (7) can be used for the calculation of the parameters for the first part of the two-section fiber,

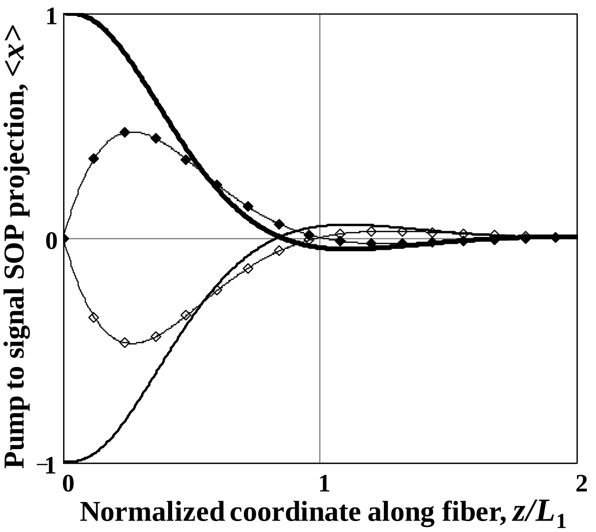

Figure 4. Evolution along the fiber length of the signal-to-pump SOP projection <x> for the case of the fiber without spinning. Minimum PDG: empty and filled diamonds; maximum PDG: thick and thin solid lines. Projections for the maximum gain: thick solid line, filled diamonds; for the minimum gain: thin solid line, empty diamonds. Parameters: $D_p^{(1)}$ = 0.1 ps·km$^{-1/2}$, L_c = 5 m, L = 50 km, α_s = 0.2 dB/km, λ_p = 1460 nm, λ_s = 1550 nm, g = 2.3 W^{-1}km^{-1}, P = 0.5 W.

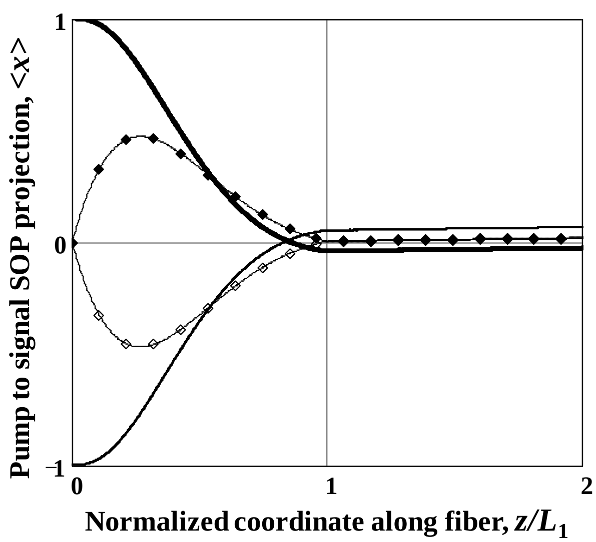

Figure 5. Evolution along the fiber length of the signal-to-pump SOP projection <x> for the case of the two-section fiber comprising a fiber without spin and a periodically spun fiber (dashed line). Minimum PDG: empty and filled diamonds; maximum PDG: thick and thin solid lines. Projections for the maximum gain: thick solid line, filled diamonds; for the minimum gain: thin solid line, empty diamonds. Parameters: $D_p^{(1)}$ = 0.1ps·km$^{-1/2}$, L_c = 5 m, $L_1 \approx$ 56.25 m, L = 50 km, α_s = 0.2 dB/km, λ_p = 1460 nm, λ_s = 1550 nm, g = 2.3 dB W^{-1}km^{-1}, P = 0.5 W , p = 0.51 m.

which leads to the minimum PMD value in the two-section fiber. As a result, we obtained optimal parameters for the first section of the fiber as $D_p^{(1)}$ = 0.1ps·km$^{-1/2}$, L_c = 5 m, $L_1 \approx$ 56.25 m (dashed line in Fig. 3). We use these parameters to calculate the evolution of pump-to-signal SOP projection <x> along the fiber without spinning (Fig. 4).

As follows from Fig. 4, the length at which the projections merge depends on the input pump SOP: it coincides with the optimal length of fiber L_1 for the pump equally shared between the PSPs at the input, and it is slightly less than L_1 for the input pump SOP oriented along the PSP. Thus, the projections will be the same from the input to the output of the second section of the fiber only for minimum PDG (Fig. 5). For the pump SOP providing maximum PDG, projections corresponding to the maximum and minimum gain <$x_{\max}$> and <$x_{\min}$> are swapped for the second section (Fig. 5). In view of $PDG \approx \langle x_{max}\rangle$-$\langle x_{min}\rangle$ and the different dependence of $\langle x_{max}\rangle$ and $\langle x_{min}\rangle$ on spinning amplitude A_0 and period p, PDG can vary from 0.005 dB to 0.2 dB for different fiber spinning amplitudes (Fig. 6). We used parameters $D_p^{(1)}$ = 0.1ps·km$^{-1/2}$, L_c = 5 m, $L_1 \approx$ 62.8 m and spinning period of p = 0.51 m in addition to the parameters mentioned above, to calculate PMD and PDG values for the two-section fiber (without spin /periodically spun) as a function of spinning amplitude A_0 based on Eqs. (6) and (9). The beat length calculated from Eq. (10) results in L_b = 2.6 m and so $(p/L_b)^2 \ll 1$. Thus, the FMM model of random birefringence is valid for our case. The results are shown in Fig. 6.

Finally, we calculated PMD and maximum/minimum PDG for a periodically spun fiber in the case of application of a depolarizer with degrees of polarization DOP = 1% and 10% with the help of Eqs (9) and accounting for changing the parameter in Eqs. (9) as follows: $\varepsilon_1 \rightarrow \varepsilon_1 DOP$ (Fig. 6). As follows from [16], temperature fluctuations can lead to an increased DOP for the input pump wave of 10-15%. In addition, the averaged values of DOP can be of 5% with insertion losses of 1.5 dB [18]. In view of this, it can lead to an increased PDG value above 1 dB (Fig. 6) and suppressed averaged gain of 1.5 dB [18].

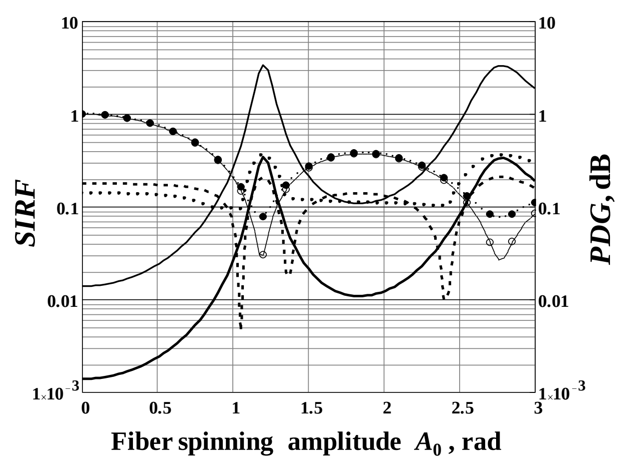

Fig. 6 SIRF (filled and empty circles) PDG (solid, dotted, and dashed lines) as a function of fiber spinning amplitude A_0. SIRF for periodically spun fiber: empty circles; two-section fiber: filled circles. PDG for two-section fiber: pump SOP along PSP (dashed line), pump is equally shared between input PSPs (dotted line). PDG for the case of depolarizer application: output DOP for depolarizer 1% (thin line), output DOP for depolarizer 10% (thick line). Parameters: $D_p^{(1)}$ = 0.1 ps·km$^{-1/2}$, L_c= 5 m, $L_1 \approx$ 56.25 m, L = 50 km, α_s = 0.2 dB/km, λ_p = 1460 nm, λ_s = 1550 nm, g = 2.3 dB W^{-1}km^{-1}, P = 0.5 W, p = 0.51 m.

TABLE I
TWO-SECTION APPROACH VS APPLICATION OF DEPOLARIZER

Specifications	Two-section approach	Application of Depolarizer
PDG	0.003 – 0.3 dB (Fig. 6)	0.3 – 3 dB (Fig. 6)[a]
Min SIRF	0.007 (Fig. 6)	0.003 (Fig. 6)
Insertion losses	< 0.2 dB	1.5 dB [18]
Mean-square gain fluctuations	2-6%	0.4-0.6%

[a]$PDG \geq 1$ dB dB for averaged output depolarizer DOP = 5% [18].

To complete the comparative analysis of the two-section technique and application of a depolarizer, we calculated also mean-square gain fluctuations for both cases with the help of Eqs. (9), (11), and (12) and notations to Eqs. (12). We find that the signal fluctuations at the input of the first section are negligible and do not exceed of 0.1%, while MSGF for the second section are within 20-60%. Application of depolarizer with DOP = 10% shows MSGF within 4-6%. In view of the notations to Eqs. (12) and the results of [17], MSGF can be suppressed approximately 10 times, i.e., to 2-6% for the two-section approach and to 0.4-06 % for the case of depolarizer application, for PMD value of $D_p^{(1)} = 0.003 \text{ps}\cdot\text{km}^{-1/2}$ (phase-matching condition $A_0 \approx 1.2$ and spinning period of $p = 0.5$ m).

Thus, the suggested cost-effective approach to simultaneous mitigation of PMD and PDG based on two-section (without spin/periodically spun) fibers shows much better results in PDG and insertion losses and slightly worse results for mean square gain fluctuations as compared to the case of depolarizer application. The results of the comparative analysis are summarized in Table I.

V. CONCLUSION

In conclusion, we report a cost-effective approach to design a quasi-isotropic transmission medium of 50 km length with a distributed Raman amplifier which demonstrates much lower polarization dependent gain as compared to the approach of application of a depolarizer.

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